

## **Holocene Faulting of the Cerro Goden Fault, western Puerto Rico**

Collaborative Research with Judith Zachariasen  
and University of Puerto Rico at Mayagüez

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### ***Introduction***

The objective of this research is to determine the level of activity of the Cerro Goden Fault in western Puerto Rico. Puerto Rico lies within the complex plate boundary zone between the North American and Caribbean plates. It is bounded by numerous large offshore structures that accommodate most of the plate boundary motion, have been the site of several M7 or greater historical earthquakes, and thus pose a significant seismic hazard to the island (Figure 1). Little work to date, however, has been done in identifying and assessing the seismic potential of onshore faults. Several large bedrock faults occur on the island of Puerto Rico, but their Quaternary history has been largely undetermined. Studies examining plate motion rates have concluded there is little onshore active faulting (e.g. Jansma et al., 2000), so most hazards assessments include little or no contribution from onshore sources. However, recent paleoseismic studies on the Lajas fault in southwestern Puerto Rico have shown that it has experienced Holocene activity raising the possibility that other heretofore unstudied faults are also active (Prentice and Mann, 2005).

The Cerro Goden fault, which runs along the base of the Cadena de San Francisco range north of Añasco in western Puerto Rico and joins with the Great Puerto Rican Southern Fault Zone, bounds the northern part of the Añasco valley, which is the site of abundant seismicity (Figure 2). More than 600 shallow earthquakes have been recorded in this region since 1987 (Abreu et al., 2004). Mayaguez, the third largest city in Puerto Rico, lies just south of the Añasco Valley. Characterizing the activity of the Cerro Goden fault is necessary to assessing the seismic hazard facing Mayaguez, and preliminary evidence has suggested the fault may be active. Offshore bathymetric and seismic reflection studies indicate that there is a fault offshore and on strike with the projection of the Cerro Goden fault. This offshore fault disrupts Holocene sediments and the sea floor from the

coast into the Mona Passage to the west (Grindlay et al., 2000; Grindlay et al., 2005). Field and air photo investigations show evidence of Quaternary faulting in at least the western reaches of the Cerro Goden fault (Mann et al., 2005). This project aims to acquire information to help characterize the activity of the Cerro Goden fault through paleoseismic trenching investigations.

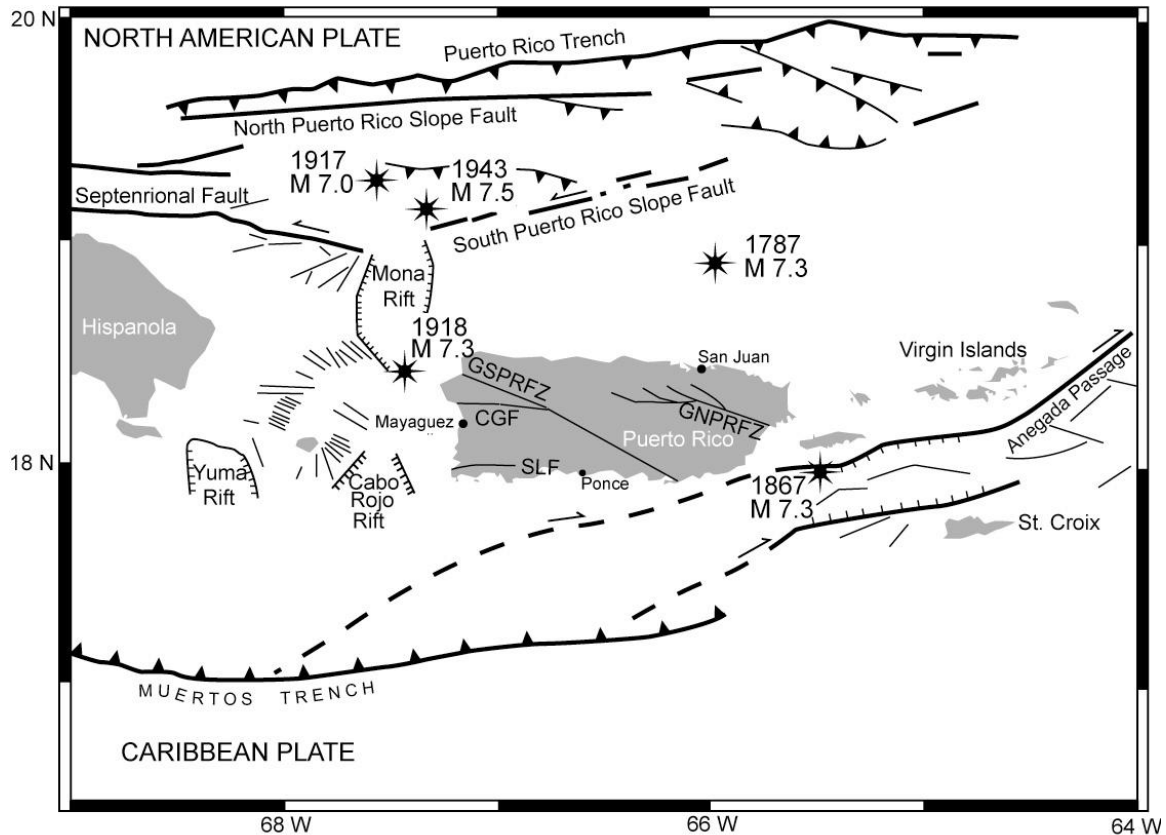


Figure 1. Tectonic setting of Puerto Rico showing major tectonic structures (modified from Jansma et al., 2000, Van Gestel et al., 1998, and Prentice and Mann, 2005). Stars represent approximate locations of epicenters of large-magnitude historical earthquakes. GNPFRFZ, great northern Puerto Rico fault zone; GSPRFZ, great southern Puerto Rico fault zone; CGF, Cerro Goden Fault; SLF,

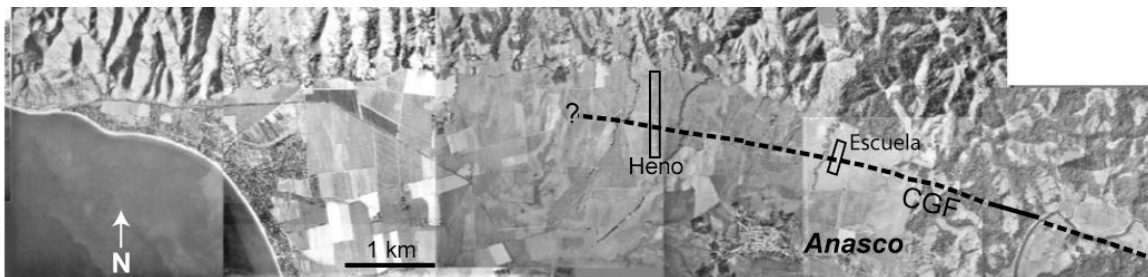


Figure 2. Composite of 1936 air photos of the northern Anasco Valley. Dark line depicts the Cerro Goden fault, solid where it occurs in bedrock exposures, and dashed where inferred in Quaternary alluvium. Note that the range front escarpment is several hundred meters north of the mapped fault, implying significant scarp erosion and retreat. Also shown are Heno and Escuela sites of 2004 high resolution seismic surveys, and 2004-2005 paleoseismic trench excavations.

### *Investigations Undertaken*

Investigations undertaken prior to this project include high-resolution seismic and paleoseismic trenching studies in the Añasco Valley. In March 2004, high-resolution seismic surveys were carried out by USGS researchers at two sites near the town of Añasco, northeast of Mayaguez. From air photos and satellite images, we had identified several likely locations of Quaternary faulting overlying the projected trace of the Cerro Goden bedrock fault, and the lines were sited to traverse these locations. One line (at the western “Heno” site) was 1200 m long, and the eastern line (“Escuela” site) was about 420 m long (Figure 2). The seismic results indicated disruptions of sediment in several locations at both the Heno and Escuela sites. These disruptions, which are consistent with faulting, appeared to exist from depth all the way to the surface and thus could indicate the occurrence of Holocene faulting.

On the basis of the seismic reflection data, we excavated trenches across two of the identified disruptions at the Escuela site in March and April 2004. One trench (Escuela 1 [ES1]) revealed a sequence of Holocene debris flow from hills to the north and quiet water sediments that lapped up on a buried scarp of probably Pleistocene weathered red clay and gravel. No fault was exposed in the trench, but we suspected that the hill of Pleistocene material, which occurs at the disruption site identified in the seismic study, could have been upthrown by faulting, creating an uphill facing scarp and that has been buried by Holocene sediments. The second trench (Escuela 2 [ES2]) revealed a sequence of fine Holocene sediments that are probably fluvial overbank deposits juxtaposed across a sub-vertical boundary against the same weathered red clay and gravel. Truncation of beds, bending of Holocene beds as they approach the contact, vertically rotated pebbles, and clay seams that could be shears suggested that the vertical contact is a fault that has displaced Holocene sediments, although we could not rule out the possibility that the stratigraphic relations were fluvial. We concluded that Holocene activity of the Cerro Goden fault was likely.

The current project was designed to examine the Cerro Goden fault further for definitive evidence for or against Holocene activity through additional trenches excavated across the features identified in the seismic lines at the Heno site. In March and April 2005, we excavated 5 trenches located above three such features. In addition, we returned to the Escuela site and reexcavated and deepened the 2004 trench that had the subvertical contact that we had interpreted as a probable fault.

We excavated the following trenches in 2005:

Heno 0 (H0): This trench was 10 m long and about 2 m deep, and located along the trace of the seismic line and over the southernmost feature identified from the seismic data. It had a north-south trend. During excavation the sediments exposed in the trench were clearly anthropogenic fill consisting of mud, silt, and straw. In addition, the trench collapsed over the projected feature during excavation, largely because the weak unconsolidated and water-saturated fill was too weak to stand even long enough to place

shores. We abandoned this trench and excavated parallel trenches about 40 m west (H4) and 100 m east (H1).

Heno 1 (H1): Because of the presence of artificial fill in our first trench (H0), which we determined was dredged from the irrigation ditch about 20 m east of the trench, we decided to excavate a parallel trench well away from the area that might be covered with deep fill. We excavated this trench about 100 m away from H0, on the other side of the ditch, centered on the projection of the feature on the seismic line along our best estimate of the fault strike. Given our uncertainty about the strike, we extended the trench on either side to encompass a wide range of strike projections. The resulting trench had a north-south trend and was 52 m long and about 2 m deep. The depth was limited by the relatively shallow water table. We logged the entire west wall and a 4 m long section of the east wall where a deep fissure was exposed, all at 1:20 scale.

Heno 2 (H2): We excavated this trench about 500 m north of trench H1, on the trace of the seismic line, and over a feature identified from the seismic data. This trench was 14 m long and about 2.5 m deep. We logged the west wall of the trench at 1:20 scale.

Heno 3 (H3): We excavated this trench about 20 m north of H2, across another identified feature. It was about 20 m long and 2.5 m deep. It had a similar stratigraphy to H2 and no signs of faulting. We did not log the trench, but photographed it to make a photomosaic showing the undeformed sediments.

Heno 4 (H4): We excavated this trench parallel to and about 40 m east of H0. The rationale was that a trench closer to the seismic line trace than H1 that might expose the features revealed in the seismic data. This trench was 30 m long and 2.5 m deep.

Escuela 2 extension (ES2): The original trench was 17 m long and 3 m deep. In 2005, we reexcavated and deepened the trench to about 4 m in the central area near the vertical contact we had tentatively identified as a probable fault.

We have submitted eleven samples for radiocarbon dating. Three of those samples contained insufficient carbon to yield an age. We have received the results for the other eight. We intend to submit two or three more samples.

## ***Results***

### Trenches

We found no faults exposed in the trenches excavated in 2005. All trenches at the Heno site revealed a suite of unfaulted, horizontally-bedded fluvial deposits. The deposits were primarily fine-grained, silt and silty clay, with sparse sand and gravel lenses. Most of the sediment was grey and brown, often with orange mottling, and several of the trenches also contained dark grey to black organic-rich horizons that suggest the now-arid area may have contained a pond or swamp at various times in the past. In addition, the southernmost three trenches (H0, H1, H4) contained a basal unit of red-orange weathered clay to clayey silt.

In 2004, the Escuela 1 trench had exposed a series of debris flow and quiet water sediments that buried a mountain-facing scarp in Pleistocene(?) clay. In the trenches located at the southern end of the Heno seismic line (H0, H1, and H4), there was also a mountain-facing scarp in the weathered orange clay. If the scarps in the three Heno trenches are the same scarp, they form a linear, approximately east-west-trending scarp subparallel to the mountain front. It is possible that a fault (or faults) that has not cut through to the surface exists below the floor of trench and has had a component of south-side-up displacement that has created the scarps at both Escuela and Heno. Another explanation for the scarp is that it represents one edge of a channel incised into the clay and subsequently filled in with fluvial sediments. If that is case, there should be another channel edge north of the one(s) exposed in our trenches. No such edge appeared in any trench. Furthermore, if the scarps are the edges of channels, the channels are very broad; flat-lying sediments were exposed for at least 20 m north of the scarp with no sign of another channel edge, nor indication that the sediments were approaching a channel edge to the north (pinching out, rising up, etc.) Finally, the exposed scarps all occurred approximately at a location above a disruption identified in the seismic data. Thus, whereas we cannot rule out a fluvial origin for the mountain-facing scarps, there is some indication that they may have been caused by a buried fault.

We reexcavated the Escuela 2 trench, originally excavated in 2004, to expose more fully the subvertical contact we suspected was a fault. We were hoping to find definitive evidence of the nature of a contact, which we did. In spite of a suite of fault-like characteristics, the bottom 5 cm of the reexcavated trench revealed the contact abruptly shallowing from near vertical to subhorizontal, indicating that it was, in fact, a fluvial contact, a buttress unconformity, rather than a fault contact. Thus, in the end, in none of the trenches at either site did we find a fault cutting the sediments in the top 2.5-4 m.

### Radiocarbon

We have so far obtained eight radiocarbon dates from four trenches. The three samples that had insufficient carbon all came from the same trench, ES1, so we have no age data from that trench at the moment.

The radiocarbon dates are all extremely young. The sample with the oldest age comes from the channel deposits of trench ES2; it has a conventional radiocarbon age of  $920 \pm 40$  BP and a calibrated date of 1020-1210 AD. The two ages from this trench are stratigraphically inverted, so clearly there are some complications with the dating. At the Heno site, some samples are also out of order, but they are also very young, all less than about 600 years. Obviously sedimentation rates are very high here. Consequently, the absence of faulting exposed in the trenches, which are mostly 2-3 m deep, does not preclude that the Cerro Goden fault has been active even in the late Holocene. However, it does indicate that, if the trenches are in fact located over strands of the fault, it has not moved in the past ca. 600 years.

### Seismic data

Because the geomorphic signature of the Cerro Goden fault is indistinct, we had used the results of the two USGS seismic reflection surveys to site our trenches. According to the interpretation of the data we obtained, there were disruptions of the sediment at several locations that extended from depth (ca 1000 m) all the way to the surface. We chose those locations to excavate our trenches. We found no fault in any trench. This brings into question the applicability of high-resolution seismic reflection and refraction for locating faults at the trench scale, since trench depths are at the limit of the precision of the seismic data. There were irregularities in the trenches at approximately the location of the disruptions in the interpreted seismic data. The coincidence of a disruption with the channel edge in trench ES2 is fortuitous; a channel edge does not continue to several hundred meters depth. The scarps in weathered clay, however, may not be channel edges but rather scarps over buried faults, which in turn could be the features identified at depth in the seismic data. In that case, the seismic data have allowed accurate location of faults in space, with just the vertical extent in question. Conversely, there could be problems with the seismic data and/or interpretation that led to our not excavating the trenches over the faults at all. In that case, we found no fault not because our trenches were too shallow to expose it, but because the trenches were mislocated north or south of it.

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### ***Non-technical Summary***

We excavated several trenches across possible traces of the Cerro Goden fault in the Añasco valley of western Puerto Rico to investigate the Holocene earthquake history of the fault. We found no fault in any of the trenches, although a subsurface scarp in several trenches may have been caused by displacement on a buried fault. The sediments in the trench are very young, less than 600-900 years old. If the trenches were accurately located over fault traces, this indicates that those traces have not experienced surface faulting in the past 600 years.

### ***Reports published***

None to date

### ***Data availability***

Trench logs available from the author.